Probing physics behind the electroweak symmetry breaking at future gravitational wave interferometers and future collider experiments

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Why does the Universe accelerate?
-Exhaustive study and challenge for the future
March 8, 2017 @ KEK

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- References:
  - MK, Kanemura, Matsui, PRD92, no.11,115007 (2015), arXiv:1509.08394
  - Hashino, MK, Kanemura, Matsui, PRD94, no.1, 015005 (2016), arXiv:1604.02069
  - Hashino, MK, Kanemura, Ko, Matsui, PLB766, 49 (2017), arXiv:1609.00297

Contents

Motivation

Discovery of the 125 GeV Higgs boson h at the CERN LHC

- The Standard Model (SM) has been established as a low-energy effective theory below $O(100)$ GeV

This is not the end of the story

Puzzles in the Higgs sector

- Guiding principle?
- Shape of the Higgs potential (multiplets, symmetries, ...)?
- Dynamics behind the electroweak symmetry breaking (EWSB)?

Phenomena beyond the SM (BSM)

- Baryon asymmetry of the Universe (BAU)
- Existence of dark matter
- Cosmic inflation
- Neutrino oscillations

Idea: Higgs sector = Window to New Physics

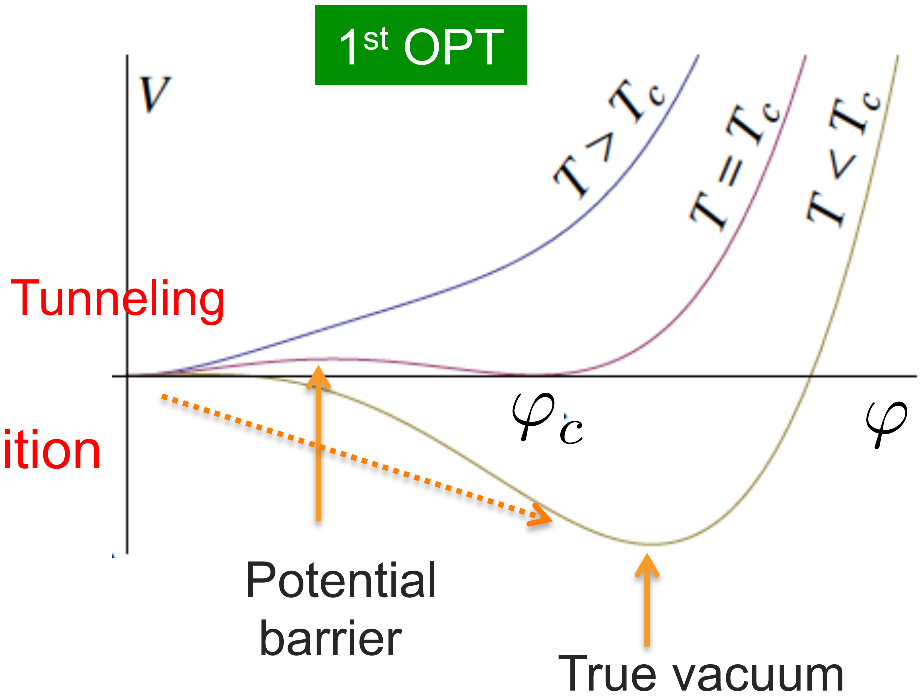
- The structure of the Higgs sector is related to BSM models

Information on new physics can be obtained by investigating the properties of the Higgs sector

Electroweak baryogenesis (EWBG) and Higgs boson couplings

Sakharov's conditions for BAU

1. Baryon number violation
   - Sphaleron process
2. Violation of C and CP
   - Extended Higgs sector
3. Departure from thermal equilibrium
   - Strongly first order phase transition (1st OPT): $\varphi_c/T_c \gtrsim 1$



SM Higgs sector w/ one doublet:

- Electroweak phase transition (EWPT) is NOT of 1st order for $m_h = 125\ \mathrm{GeV}$

EWBG is an important physics case relating the Higgs sector to BSM phenomena

Strongly 1st OPT and Higgs boson couplings

Models with extended Higgs sector

- 1st OPT can be easily realized
- Signatures are testable at colliders

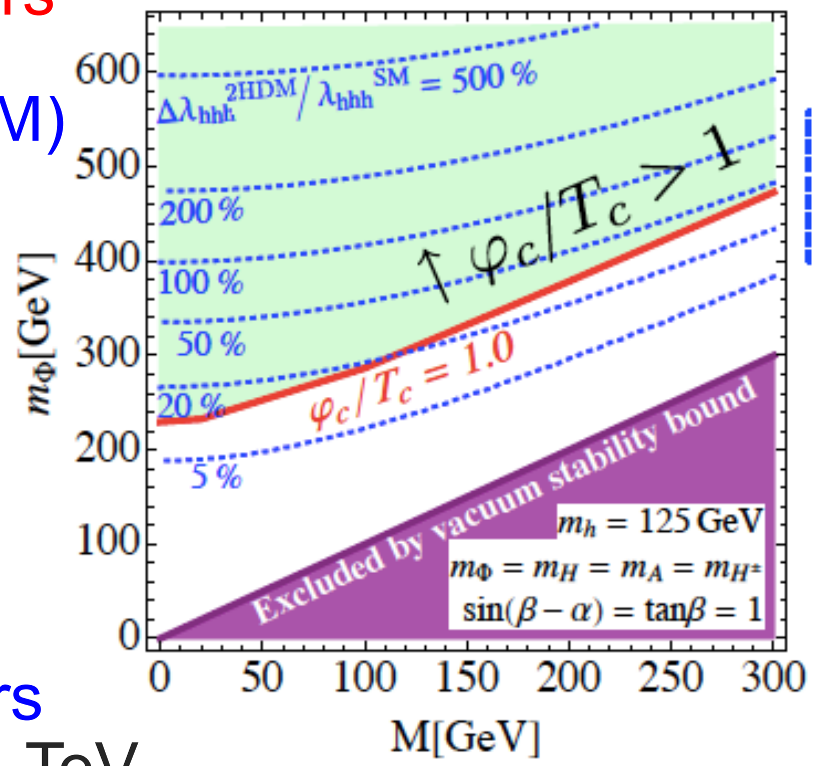
e.g. Two Higgs doublet model (2HDM)

- Condition for strongly 1st OPT:

$$\varphi_c/T_c \gtrsim 1$$

➡ Large deviation in the triple Higgs boson coupling

$$(\Delta\lambda_{hhh}/\lambda_{hhh}^{\rm SM} \gtrsim 10\%)$$



[Kanemura, Okada, Senaha (2005)]

EWBG can be tested at future colliders

- International Linear Collider (ILC) 1 TeV w/ $L = 5\ {\rm ab}^{-1}$ can measure λ_{hhh} at 10% accuracy [Fujii et al. (2015)]

Gravitational waves (GWs) as a probe of EWPT

Ground-based interferometers (aLIGO, KAGRA, aVirgo)

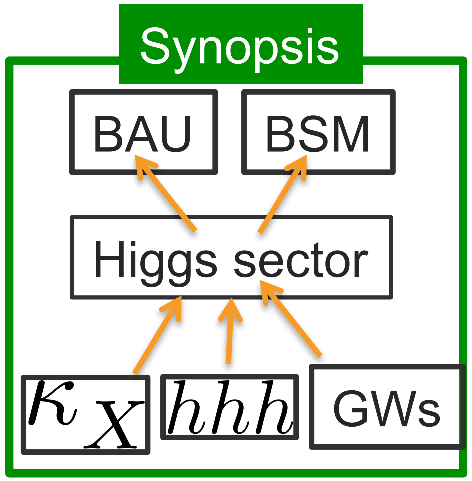
- Targets: GWs from binary systems, supernovae, ...
- aLIGO made the first direct observation of GWs

  ➡ New era of GW astronomy [LIGO and Virgo (2016)]

Future space-based interferometers (LISA, DECIGO)

- Sensitive to GWs from the early Universe (Strongly 1st OPT, cosmic inflation, ...)

  ➡ New era for fundamental physics



Goal:

- To investigate testability of models of EWSB using the synergy between the measurements of the GWs, Higgs boson couplings κ_X and the hhh coupling

Contents

Studies on the GWs from 1st order EWPT

Model independent analysis

[Grojean, Servant (2007); Kikuta, Kohri, So (2014), ...]

Higgs potential with higher order operators

[Delaunay, Grojean, Wells (2008); Huang, Wan, Wang, Cai, Zhang (2016), ...]

Non-decoupling loop effects from hypothetical particles

- Additional (Higgs) scalar loop effects
  [MK, Kanemura, Matsui (2015); Hashino, MK, Kanemura, Matsui (2016), Dorsch, Huber, Konstandin, No (2016), ...]
- Light stop loop effects in the MSSM
  [Apreda, Maggiore, Nicolis, Riotto (2002), ...]

n.b. Light stops are excluded by LHC

Non-thermal effects even at the tree level

- Real singlet extension
  [Ashoorioon, Konstandin (2009); Huang, Long, Wang (2016); Hashino, MK, Kanemura Ko, Matsui (2016), ...]
- Next-to-MSSM
  [Apreda, Maggiore, Nicolis, Riotto (2002), Huber, Konstanding (2007); Huber, Konstandin, Nardini, Rues (2015), ...]

Model A: Models with additional singlet scalars (without CSI)

Idea: [MK, Kanemura, Matsui (2015)]

- To generally handle strongly 1st OPT via thermal loop, N isosinglet scalars $S_i \, (i = 1, \cdots, N)$ are introduced
- For simplicity, $O(N)$ symmetry is imposed

Tree-level scalar potential: $V_0(\Phi, \vec{S}) = V_{\rm SM}(\Phi) + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$

Singlet scalar boson mass: $m_S^2 = \mu_S^2 + \frac{\lambda_{\Phi S}}{2}v^2$

Triple Higgs boson coupling:

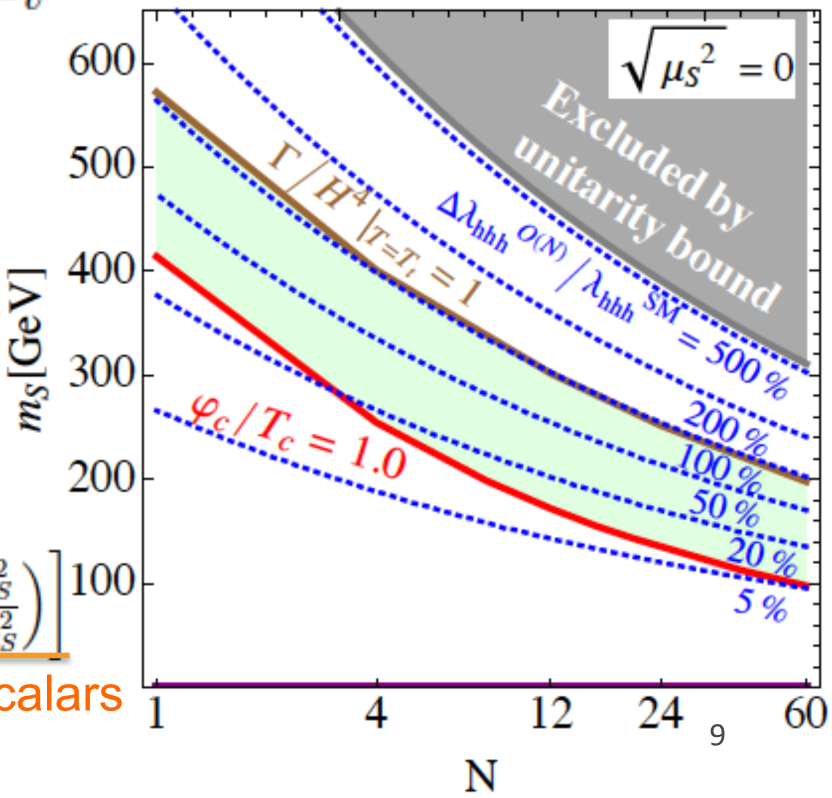
$$\lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v}\left\{1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2} + \frac{N}{12\pi^2}\frac{m_S^4}{v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3\right\}$$

Finite temperature effective potential (high temperature expansion):

$$V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\frac{\varphi_c}{T_c} \propto E = \frac{1}{12\pi v^3}\left[6m_W^3 + 3m_Z^3 + N m_S^3\left(1 - \frac{\mu_S^2}{m_S^2}\right)\left(1 + \frac{3\mu_S^2}{2m_S^2}\right)\right]$$

Non decoupling loop effect from additional scalars



Model B: CSI models with additional singlet scalars

Idea [Hashino, Kanemura, Orikasa (2015)]

- Mass parameters are absent in the original Lagrangian due to Classical Scale Invariance (CSI) [Bardeen (1995)]
- EWSB is directly caused by thermal loop effects

Tree-level scalar potential

$$V_0(\Phi, \vec{S}) = \frac{\lambda}{2}|\Phi|^4 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$$

Singlet scalar boson mass

$$N m_S^4 = 8\pi^2 v^2 m_h^2 - 6m_W^4 - 3m_Z^4 + 12m_t^4$$

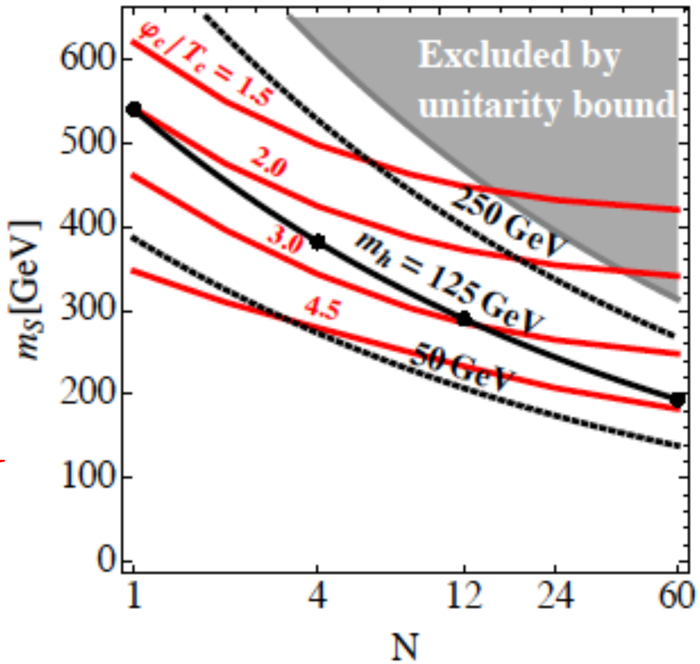
Triple Higgs boson coupling

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM(tree)}}} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM(tree)}}} - 1 = \frac{2}{3}$$

independent of N

[Hashino, Kanemura, Orikasa (2015)]

φ_c/T_c



[Hashino, MK, Kanemura, Matsui (2015)]

Model C: Higgs singlet model

Idea

[Hashino, MK, Kanemura, Ko, Matsui (2016)]

- To investigate strongly 1st OPT and Higgs couplings induced through Higgs field mixing (at least 2 classical fields needed)
- For simplicity, we introduce a singlet Higgs field S

Tree-level Higgs potential

$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

$\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\varphi_\Phi \end{pmatrix}$: SM Higgs doublet

$\langle S\rangle = \varphi_S$: Higgs singlet

Effective potential:

$$V_{\text{eff},T=0}(\varphi_\Phi, \varphi_S) = V_0(\varphi_\Phi, \varphi_S) + \sum_i n_i \frac{M_i^4(\varphi_\Phi, \varphi_S)}{64\pi^2}\left(\ln\frac{M_i^2(\varphi_\Phi, \varphi_S)}{Q^2} - c_i\right)$$

$c_F = c_S = 5/6$
$c_V = 5/6$

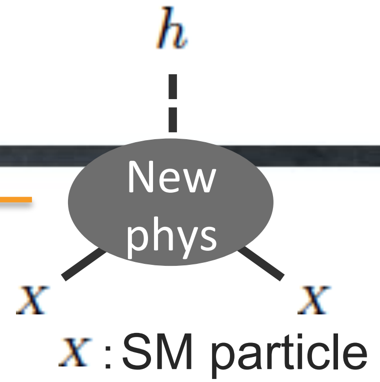
Higgs boson masses and mixing

$m_h (= 125\ \mathrm{GeV})$: Mass of the discovered Higgs boson

m_H : Mass of the additional Higgs boson

θ : Higgs mixing angle

Model C: Higgs Singlet Model (contd.)



Higgs boson couplings to SM particles $\kappa_X = \dfrac{g_{hXX}}{g_{hXX}|_{\rm SM}}$

$$\kappa = \kappa_V = \kappa_F = \cos\theta$$

Triple Higgs boson couplings (effective potential approach)

$$\Delta\lambda_{hhh} = \frac{\lambda_{hhh}^{\rm HSM} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}} \qquad \lambda_{hhh}^{\rm SM} = \frac{3m_h^2}{v_\Phi}\left[1 + \frac{9m_h^2}{32\pi^2 v_\Phi^2} + \sum_{i=W^\pm,Z,t,b} n_i \frac{m_i^4}{12\pi^2 m_h^2 v_\Phi^2}\right]$$

$$\lambda_{hhh}^{\rm HSM} = c_\theta^3 \left\langle \frac{\partial^3 V_{{\rm eff},T=0}}{\partial\varphi_\Phi^3} \right\rangle + c_\theta^2 s_\theta \left\langle \frac{\partial^3 V_{{\rm eff},T=0}}{\partial\varphi_\Phi^2 \partial\varphi_S} \right\rangle + c_\theta s_\theta^2 \left\langle \frac{\partial^3 V_{{\rm eff},T=0}}{\partial\varphi_\Phi \partial\varphi_S^2} \right\rangle + s_\theta^3 \left\langle \frac{\partial^3 V_{{\rm eff},T=0}}{\partial\varphi_S^3} \right\rangle$$

Finite temperature effective potential in one direction (high temperature expansion)

$$V_{\rm eff} = D(T^2 - T_0^2)\varphi^2 - (ET - e)\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

$$\Rightarrow \quad \frac{\varphi_c}{T_c} = \frac{2E}{\lambda}\left(1 - \frac{e\lambda}{ET}\right)$$

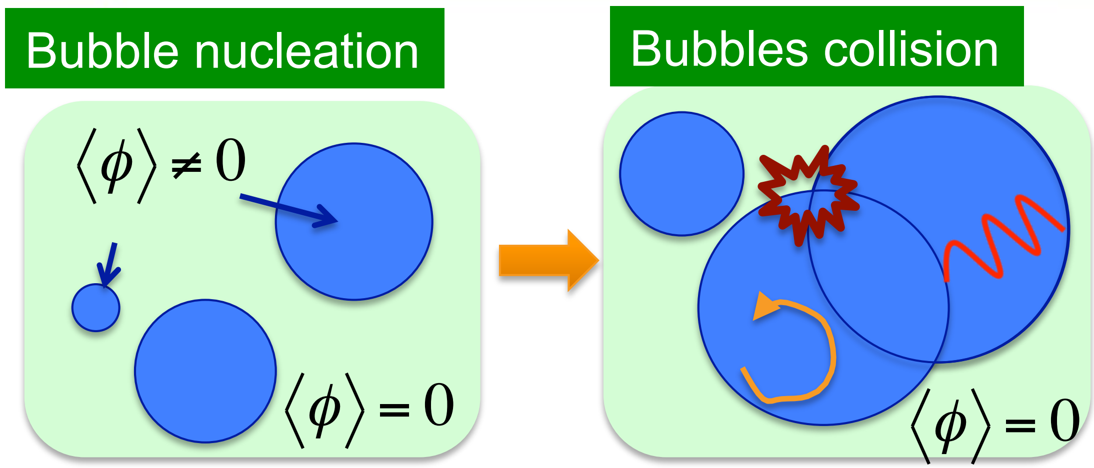
Effects from the Higgs boson mixing

The Higgs boson mixing gives considerable contributions to deviation in the Higgs boson couplings and to phase transition

Contents

1. Introduction
2. Models with extended scalar sectors
   A. Models with additional singlet scalars (without CSI)
   B. CSI models with additional singlet scalars
   C. Higgs singlet model (HSM)
3. Gravitational waves from first order phase transition
4. Synergy between measurements of gravitational waves and various Higgs boson couplings
5. Summary

Important quantities for GW spectrum



Sources of GWs

1. Collision of bubble walls
2. Compression wave of plasma
3. Plasma turbulence

- GW spectrum is derived from finite temperature effective potential $V_{\rm eff}$

Bubble nucleation rate per unit volume per unit time:

$$\Gamma(t) = \Gamma_0(t)\exp[-S_E(t)] \quad S_E(T) = S_3(T)/T \quad S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\rm eff}(\varphi_b, T)\right]$$

Transition temperature T_t :

$$\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1 \quad \Rightarrow \quad \frac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$$

Released false vacuum energy (Latent heat)

$$\epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$$

Normalized parameter: $\alpha = \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)}$

Inverse of the duration of phase transition

$$\beta = -\left.\frac{dS_E}{dt}\right|_{t=t_t} \simeq \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t}$$

Normalized parameter: $\tilde{\beta} = \frac{\beta}{H_t}$

GW spectrum

- Complicated numerical simulations are necessary
- Approximate fitting formula are available [Caprini et al. (2015)]

Collision of bubble walls (Envelope approximation):

$$\tilde{\Omega}_{\rm env} h^2 \simeq 1.67 \times 10^{-5} \times \left(\frac{0.11 v_b^3}{0.42 + v_b^2} \right) \tilde{\beta}^{-2} \left(\frac{\kappa_\phi \alpha}{1+\alpha} \right)^2 \left(\frac{100}{g_*^t} \right)^{1/3}$$

$$\tilde{f}_{\rm env} \simeq 1.65 \times 10^{-5}\ {\rm Hz} \times \left(\frac{0.62}{1.8 - 0.1 v_b + v_b^2} \right) \tilde{\beta} \left(\frac{T_t}{100\ {\rm GeV}} \right)$$

Sound waves (Compression waves of thermal plasma):

$$\tilde{\Omega}_{\rm sw} h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha} \right)^2 \left(\frac{100}{g_*^t} \right)^{1/3} \qquad \tilde{f}_{\rm sw} \simeq 1.9 \times 10^{-5}\ {\rm Hz} \frac{1}{v_b} \tilde{\beta} \left(\frac{T_t}{100\ {\rm GeV}} \right)$$

Magnetohydrodynamic (MHD) turbulence:

$$\tilde{\Omega}_{\rm turb} h^2 \simeq 3.35 \times 10^{-4} v_b \tilde{\beta}^{-1} \left(\frac{\epsilon \kappa_v \alpha}{1+\alpha} \right)^{3/2} \left(\frac{100}{g_*^t} \right)^{1/3} \qquad \tilde{f}_{\rm turb} \simeq 2.7 \times 10^{-5}\ {\rm Hz} \frac{1}{v_b} \tilde{\beta} \left(\frac{T_t}{100\ {\rm GeV}} \right)$$

- v_b : wall velocity
- κ_ϕ , κ_v and $\epsilon = 0.05$: efficiency factors

Contents

Model A: GW spectrum in $O(N)$ models without CSI

Contribution to GWs

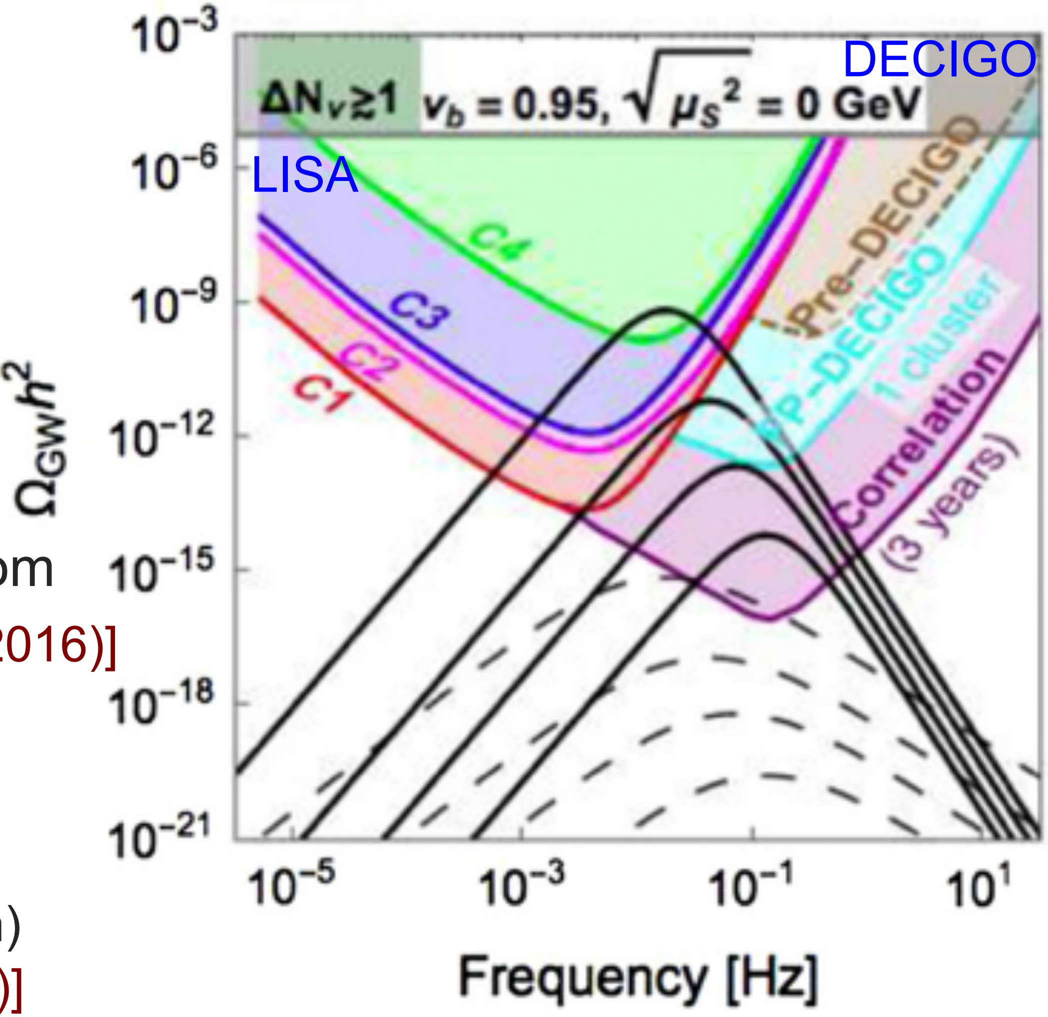
- Wall collision: ·············
- Sound wave: ———
- MHD Turbulence: - - - -

- Benchmark points:

$\Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} = 2/3$

$N = 1, 4, 12, 60$ from the bottom

[Hashino, MK, Kanemura, Matsui (2016)]



Experimental prospects:

- LISA (C1-C4)
  [Caprini et al. (2015)]
- DECIGO (Pre, FP, Correlation)
  [Kawamura et al. (2011)]

GWs from 1st order EWPT in $O(N)$ models are detectable at future space-based interferometers, LISA and DECIGO

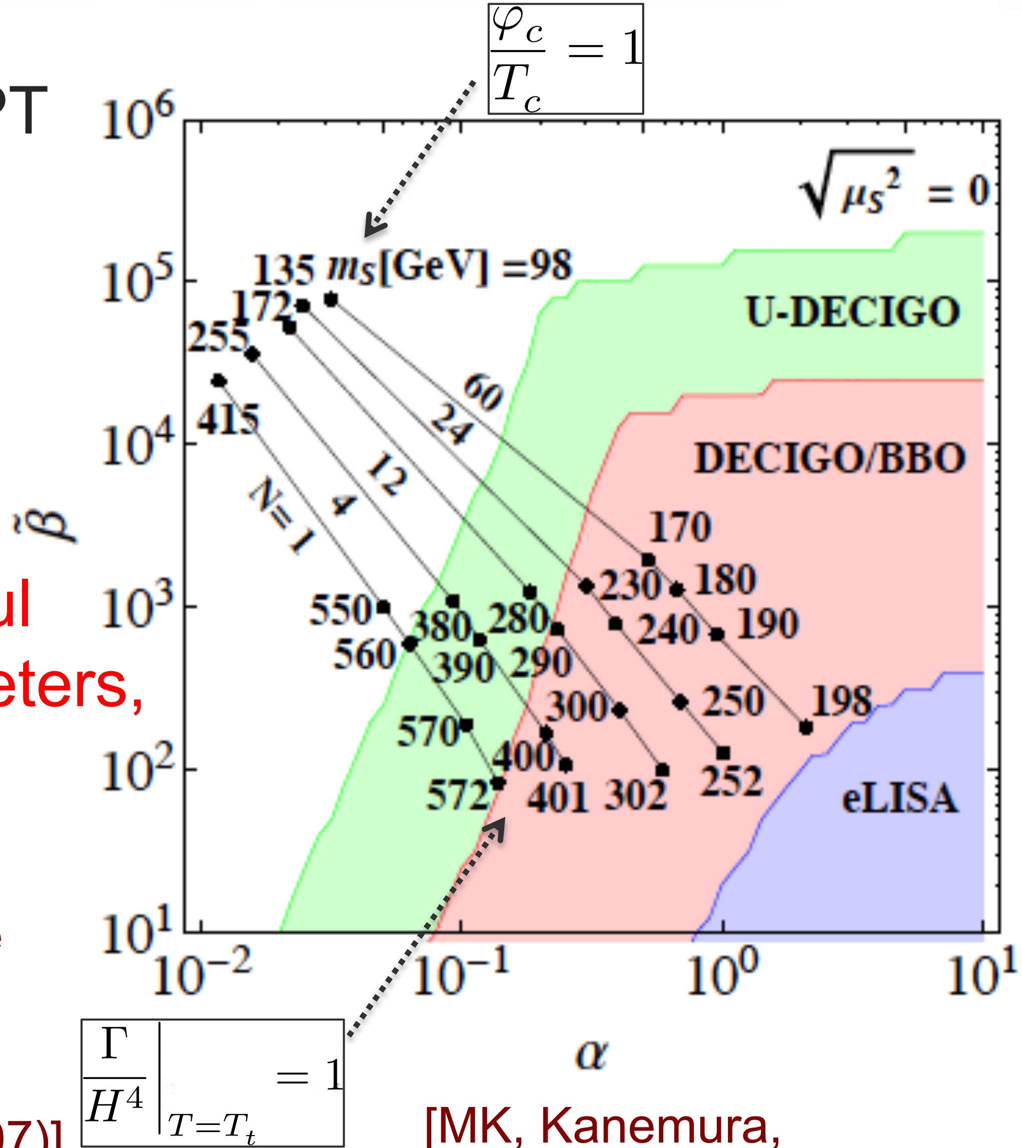
Model A: Predicted values of α and $\tilde{\beta}$

- Condition for strongly 1st OPT
  ➡ Constraints on α and $\tilde{\beta}$ for each model
  [MK, Kanemura, Matsui (2015)]

- α and $\tilde{\beta}$ to be determined by GW observation are useful in determining model parameters, such as N and m_S

n.b.: The experimental prospects are estimated based on the traditional GW spectrum

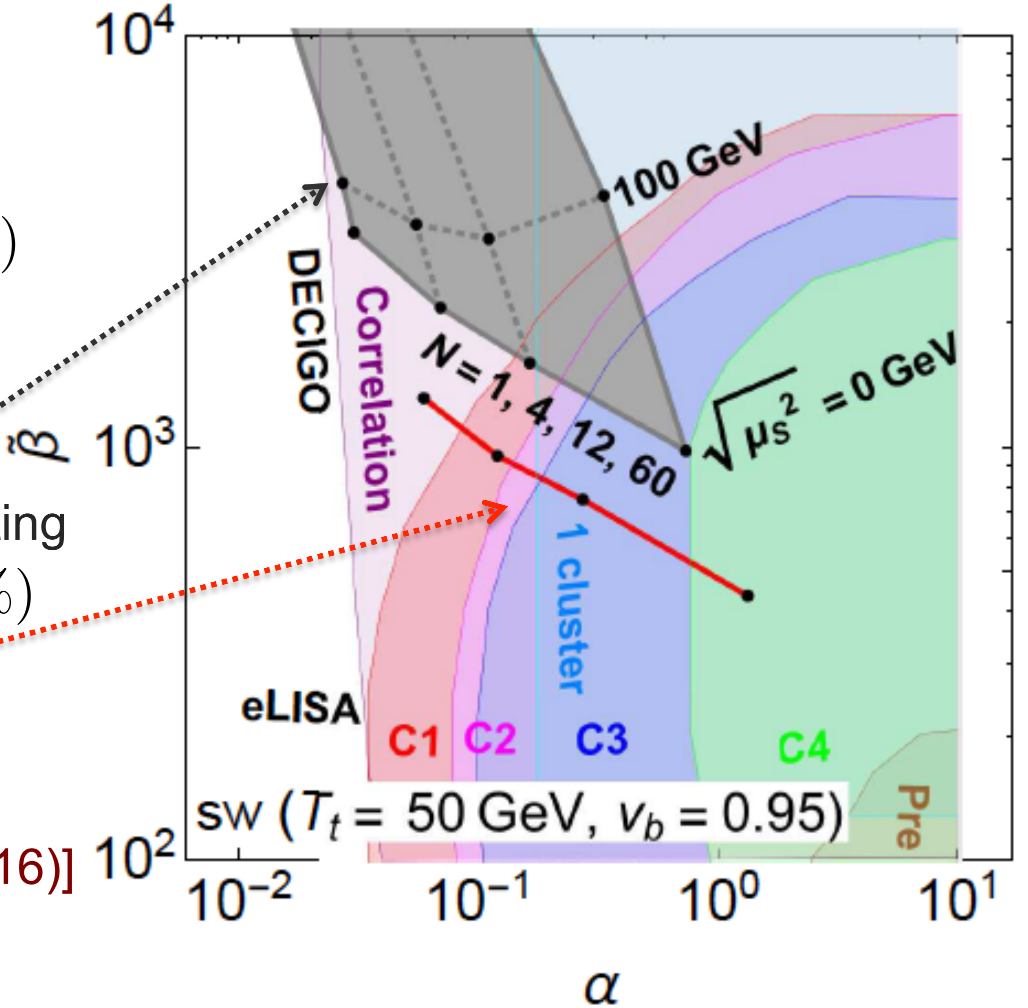
[See e.g. Grojean, Servant (2007)]



[MK, Kanemura, Matsui (2015)]

Testability of models with additional singlet scalars with and without CSI

- What if the hhh coupling is found to be
$$\Delta\lambda_{hhh}/\lambda_{hhh}^{\rm SM} = 2/3(\simeq 70\%)$$
at future colliders?



- $O(N)$ models without CSI predicting
$$\Delta\lambda_{hhh}/\lambda_{hhh}^{\rm SM} = 2/3(\simeq 70\%)$$
- CSI $O(N)$ models

[Hashino, MK, Kanemura, Matsui (2016)]

Models with and without CSI can be distinguished at future GW interferometers even if they share common hhh coupling

Model C: Predicted values of α and $\tilde{\beta}$ in the HSM

Numerical results based on the two-field analysis

- Benchmark point

v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	−80	−30	0	[160, 240]	[−45, 0]

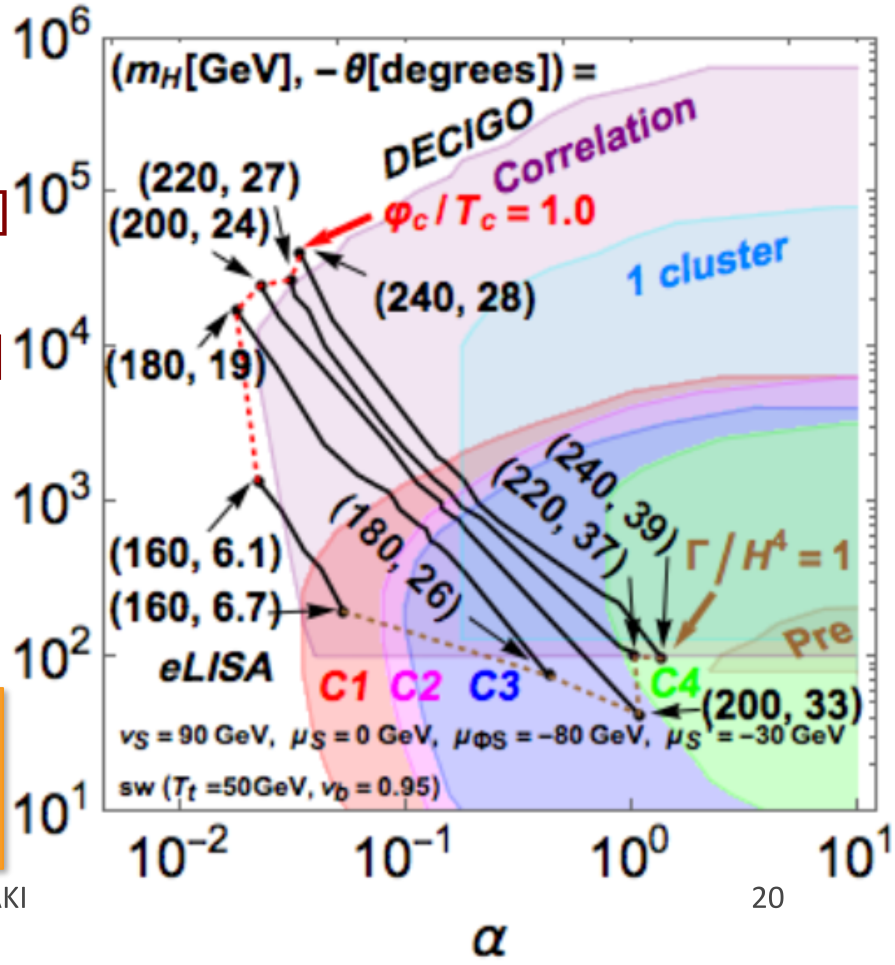
- Condition for strongly 1st OPT

  ➡ Constraints on α & $\tilde{\beta}$

[Hashino, MK, Kanemura, Ko, Matsui (2016)]

  - Implemented into CosmoTransitions

[Wainwright (2012)]



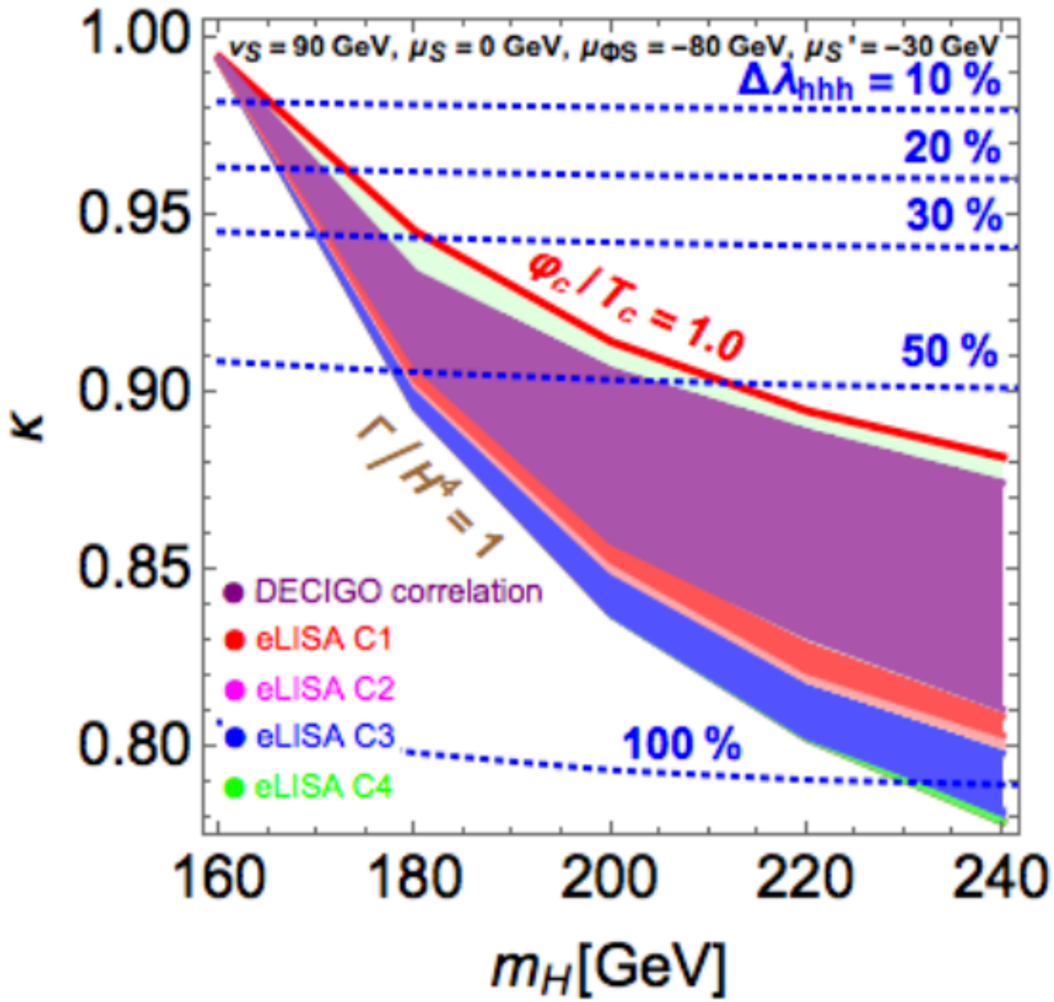
Prospects of future exps.

- eLISA (C1-C4): [Caprini et al. (2015)]
- DECIGO (Pre, 1 cluster, Correlation)
  [Kawamura et al. (2011)]

GWs from 1st OPT in the HSM are detectable at eLISA and DECIGO

Model C: Synergy of measurements of various Higgs boson couplings and GWs in the HSM

[Hashino, MK, Kanemura, Ko, Matsui (2016)]



Collider experiments

- LHC Run I results

  $\kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10}$

  [ATLAS, CMS (2016)]
- HL-LHC

  $\kappa_V : 2\%$ [CMS (2013)]
- ILC w/ $\sqrt{s} = 500$ GeV

  $\kappa_Z : 0.37\%$ $\kappa_W : 0.51\%$
- ILC w/ $\sqrt{s} = 1$ TeV

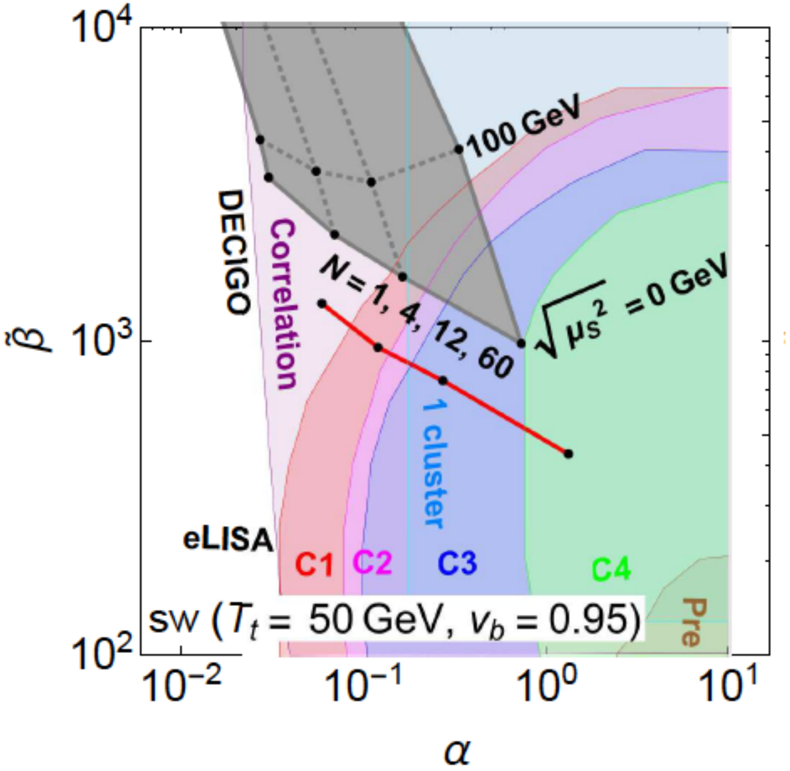
  $\Delta\lambda_{hhh} : 10\%$

  [Fujii et al. (2015)]

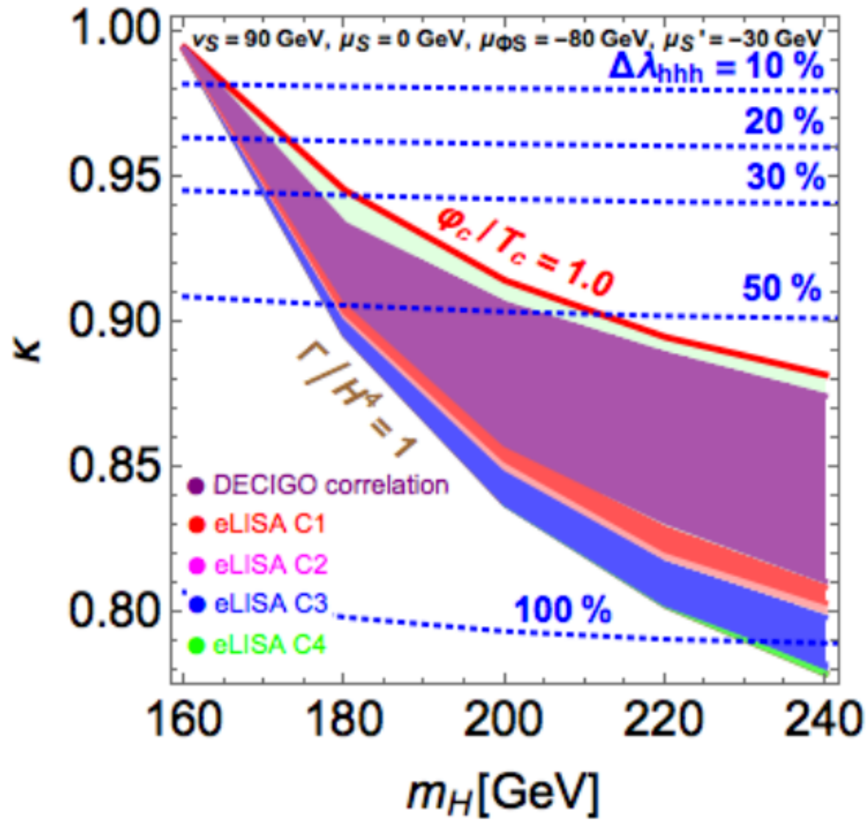
The synergy between the Higgs boson coupling measurements and GW observations is important for the HSM Higgs potential

Summary

- Models with additional singlet scalars with and without CSI



- Higgs singlet model



- The strongly 1stOPT of the EWSB in extended Higgs sectors can be tested by the synergy of the measurements of Higgs boson couplings κ_X at the LHC, the hhh coupling at the ILC and GWs at future space-based interferometers

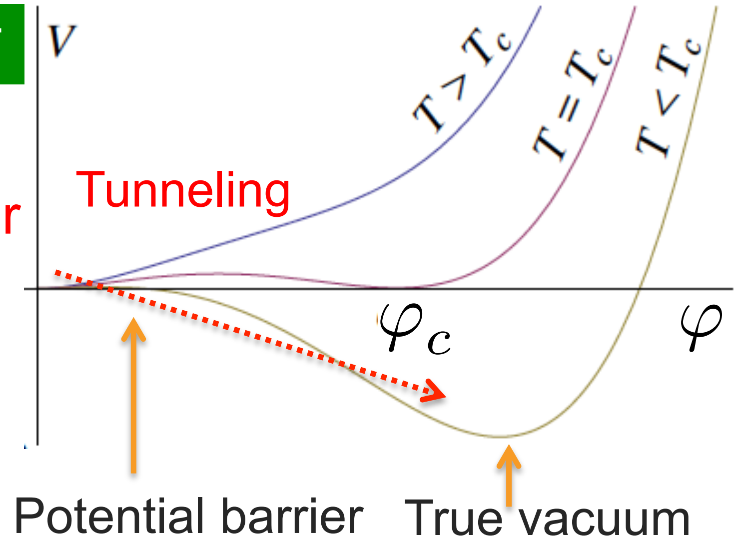
Backup slides

Electroweak baryogenesis (EWBG) and Higgs boson couplings

Sakharov's conditions for BAU

1st OPT

1. Baryon number violation ← Sphaleron
2. C and CP violation ← Extended Higgs sector
3. Departure from thermal equilibrium
   ↑ Strongly first order phase transition (1st OPT): $\varphi_c/T_c \gtrsim 1$



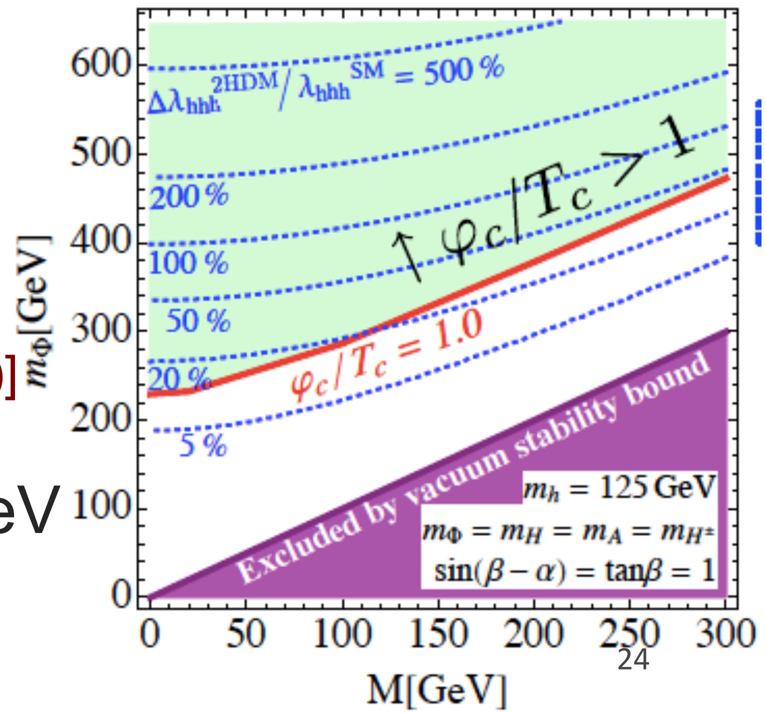
SM Higgs sector w/ one doublet:

- Electroweak phase transition (EWPT) is NOT of 1st order for $m_h = 125\ \mathrm{GeV}$

e.g. Two Higgs doublet model (2HDM)

$$\varphi_c/T_c \gtrsim 1 \rightarrow \Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} \gtrsim 10\%$$

[Kanemura, Okada, Senaha (2005)]



EWBG can be tested at future colliders

- International Linear Collider (ILC) 1 TeV can measure λ_{hhh} at 10% accuracy

[Fujii et al. (2015)]

Sketch of first order phase transition

Effective potential at one-loop level:

$$V_{\rm eff}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi)\left(\ln\frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2}\right)$$

Contribution at finite-temperatures:

$$\Delta V_T(\varphi, T) = \frac{T^4}{2\pi^2}\left[\sum_{i=\rm bosons} n_i I_B(a^2) + \sum_{i=\rm fermions} n_i I_F(a^2)\right]$$

$$I_{B/F}(a^2) = \int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+a^2}}\right) \quad a^2 = \frac{M^2(\varphi, T)}{T^2}$$

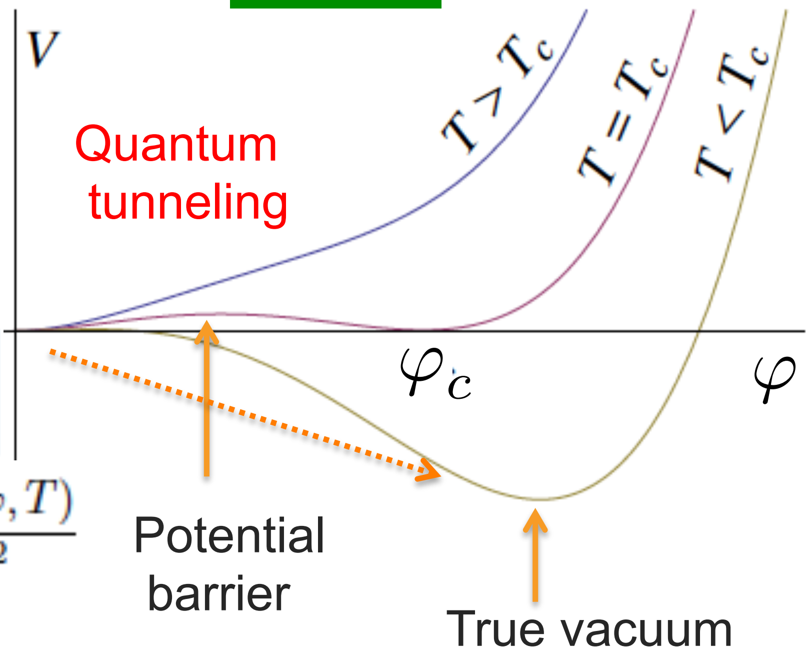
High-temperature expansion:

$$V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots \qquad \varphi_c/T_c \propto E$$

$$I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{32}\left(\ln\frac{a^2}{\alpha_B} - 3/2\right) + \mathcal{O}(a^6)$$

$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32}\left(\ln\frac{a^2}{\alpha_F} - 3/2\right) + \mathcal{O}(a^6)$$

1st OPT



Bosonic loop contribute to the cubic term

Strongly 1st OPT $(\varphi_c/T_c \gtrsim 1)$ can be achieved by adding bosons

Necessary for successful electroweak baryogenesis

Gravitational waves

Properties of gravitational waves

- GWs propagate at the speed of light
- GWs are transverse to the direction of propagation
- Spin 2
- 2 polarization modes: Plus mode h+ & Cross mode hx

Weak-field approximation:

- Metric close to flat: $g_{\mu\nu}(x) = \eta_{\mu\nu} + \underline{h_{\mu\nu}(x)}$ $|h_{\mu\nu}| \ll 1$

  Linearlized Einstein eq. in vacuum: $\Box h_{\mu\nu} = 0$ Wave eq.!

Interactions of gravitational waves

- Reaction rate: $\Gamma = n\sigma v$ $n \sim T^3$ $\sigma \sim G^2 T^2 = \frac{T^2}{M_{Pl}^4}$ $v \sim 1$
- Expansion rate of the Universe: $H \sim \frac{T^2}{M_{Pl}}$

➡ $\frac{\Gamma}{H} \sim \frac{T^3}{M_{Pl}^3}$: GWs decouple below the Planck scale M_{Pl}

GWs convey information on the time when produced

Relic gravitational waves

Characteristics of relic gravitational waves

- Isotropic
- Static
- Unpolarized

➡ Relic GWs are characterized only by frequency

Energy density of relic gravitational waves

$$\rho_{\rm GW} = \frac{1}{32\pi G}\langle \dot{h}_{ij}\dot{h}_{ij}\rangle$$

- Normalized Energy density per unit logarithmic interval of frequency f

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f} \qquad \rho_c = \frac{3H_0^2}{8\pi G}$$

: Critical density

Typical frequency of relic gravitational waves

Gravitational waves produced with frequency f_t, abundance $\Omega^t_{\rm GW}$ are red-shifted due to the expansion of the Universe

- Frequency and energy density scale as $f \propto \frac{1}{a}$ $\rho_{\rm GW} \propto \frac{1}{a^4}$
- Conservation of entropy: $sa^3 =$ const.

a : scale factor

➡ Red-shifted GW relic abundance observed today:

$$\Omega_{\rm GW} h^2 \simeq 1.7 \times 10^{-5} \left(\frac{100}{g^t_*}\right)^{1/3} \Omega^t_{\rm GW}$$

Red-shifted typical frequency observed today:

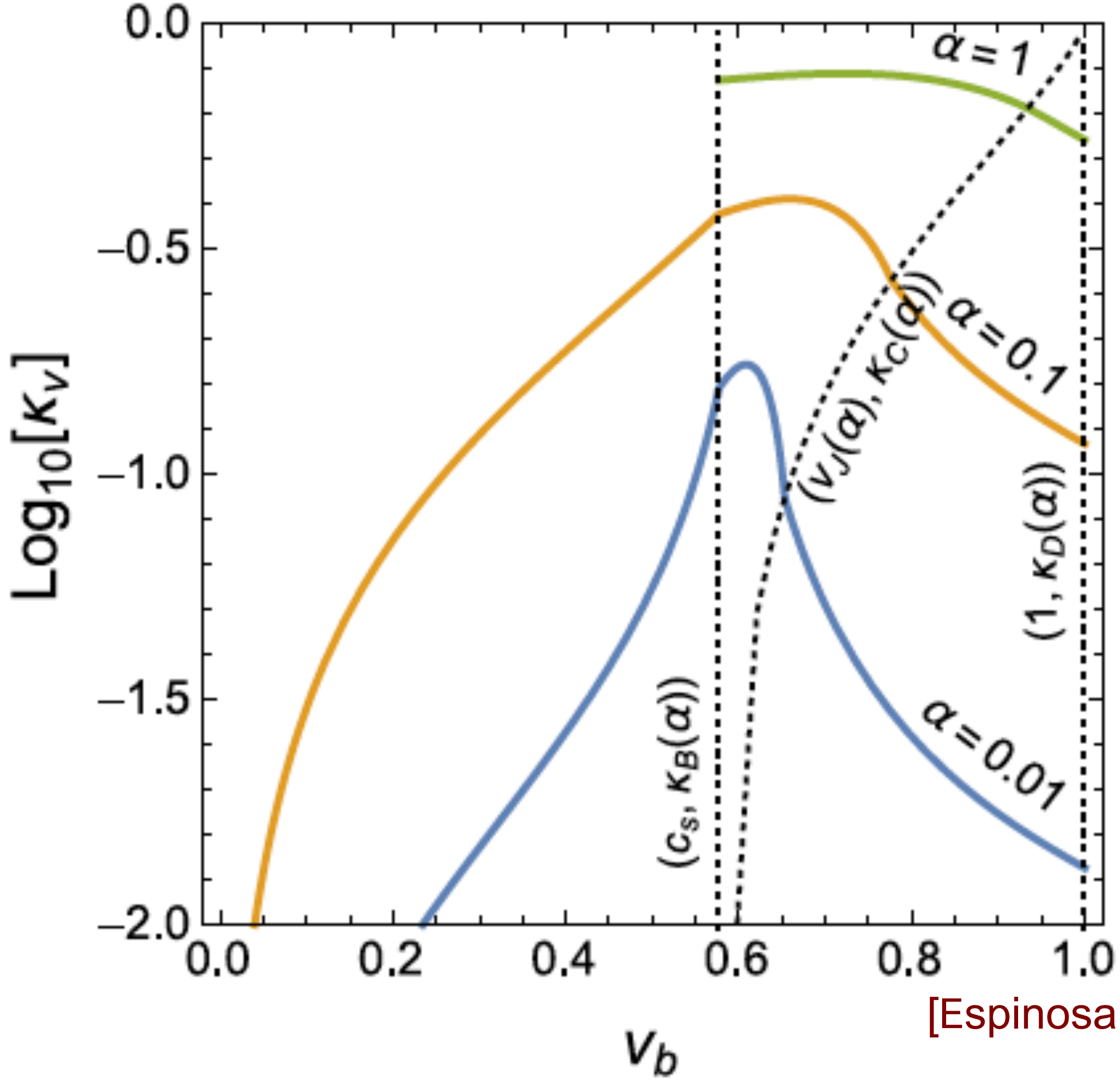
$$f_0 \simeq 1.7 \times 10^{-5} \left(\frac{g^t_*}{100}\right)^{1/6} \left(\frac{T_t}{100\ \text{GeV}}\right) \frac{f_t}{H_t}\ \text{Hz}$$

For typical electroweak phase transition:

$T_t \sim 100$ GeV $f_t/H_t \sim 10^2 - 10^4$ ➡ $f_0 \sim 10^{-3} - 10^{-1}$ Hz

Range for future space-based interferometers

Efficiency factor



[Espinosa et al. (2010)]

Models with additional singlet scalars (without CSI) (contd.)

- Effective potential: [MK, Kanemura, Matsui (2015)]

$$V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 . + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left(\ln \frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2} \right)$$

$$\Rightarrow \lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v} \left\{ 1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2} + \underline{\frac{N}{12\pi^2}\frac{m_S^4}{v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3} \right\}$$

Non decoupling loop effect from additional scalars

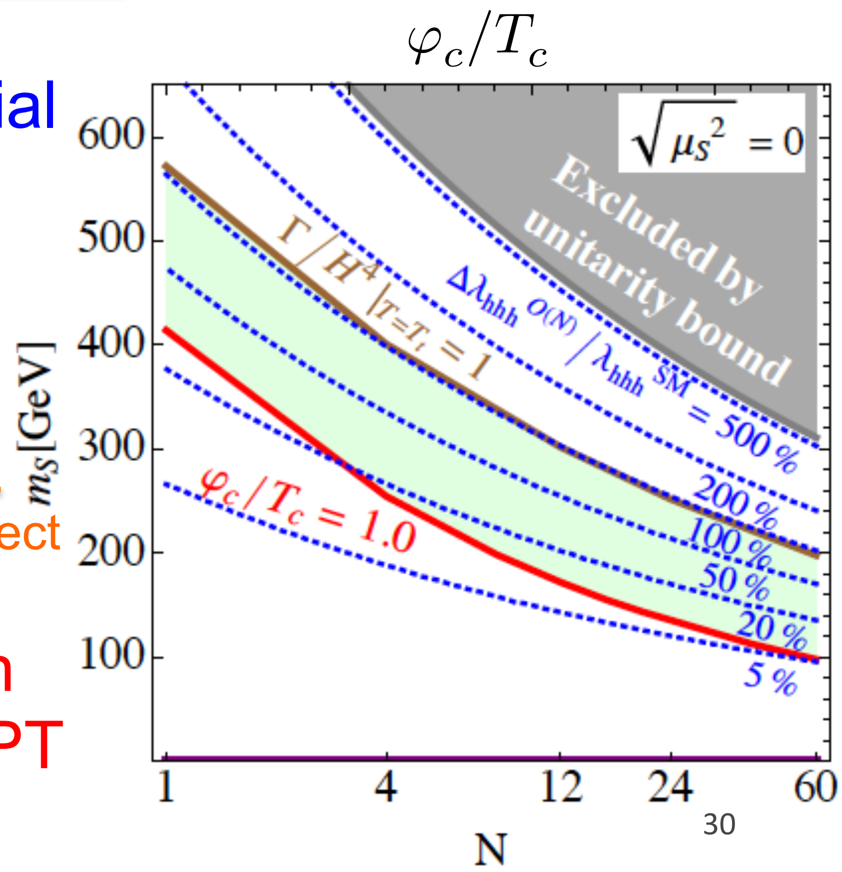
- Finite temperature effective potential (high temperature expansion):

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\frac{\varphi_c}{T_c} \propto E = \frac{1}{12\pi v^3}\left[6m_W^3 + 3m_Z^3 + \underline{N m_S^3 \left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 \left(1 + \frac{3\mu_S^2}{2m_S^2}\right)} \right]$$

Non decoupling loop effect from additional scalars

$\Rightarrow$ Typically $\mathcal{O}(10)\%$ deviation in λ_{hhh} for strongly 1st OPT



Benchmark points

- $O(N)$ models without CSI:

$\sqrt{\mu_S^2} = 0$

N	1	4	12	60
m_S	540 GeV	382 GeV	290 GeV	194 GeV
φ_c/T_c, T_c	2.01, 102 GeV	2.40, 90.1 GeV	2.91, 76.8 GeV	4.11, 56.1 GeV
$(\alpha, \tilde{\beta})$, T_t	(0.0593, 1320), 88.5 GeV	(0.120, 956), 74.3 GeV	(0.273, 705), 59.7 GeV	(1.33, 438), 38.4 GeV

$\sqrt{\mu_S^2} = 100$ GeV

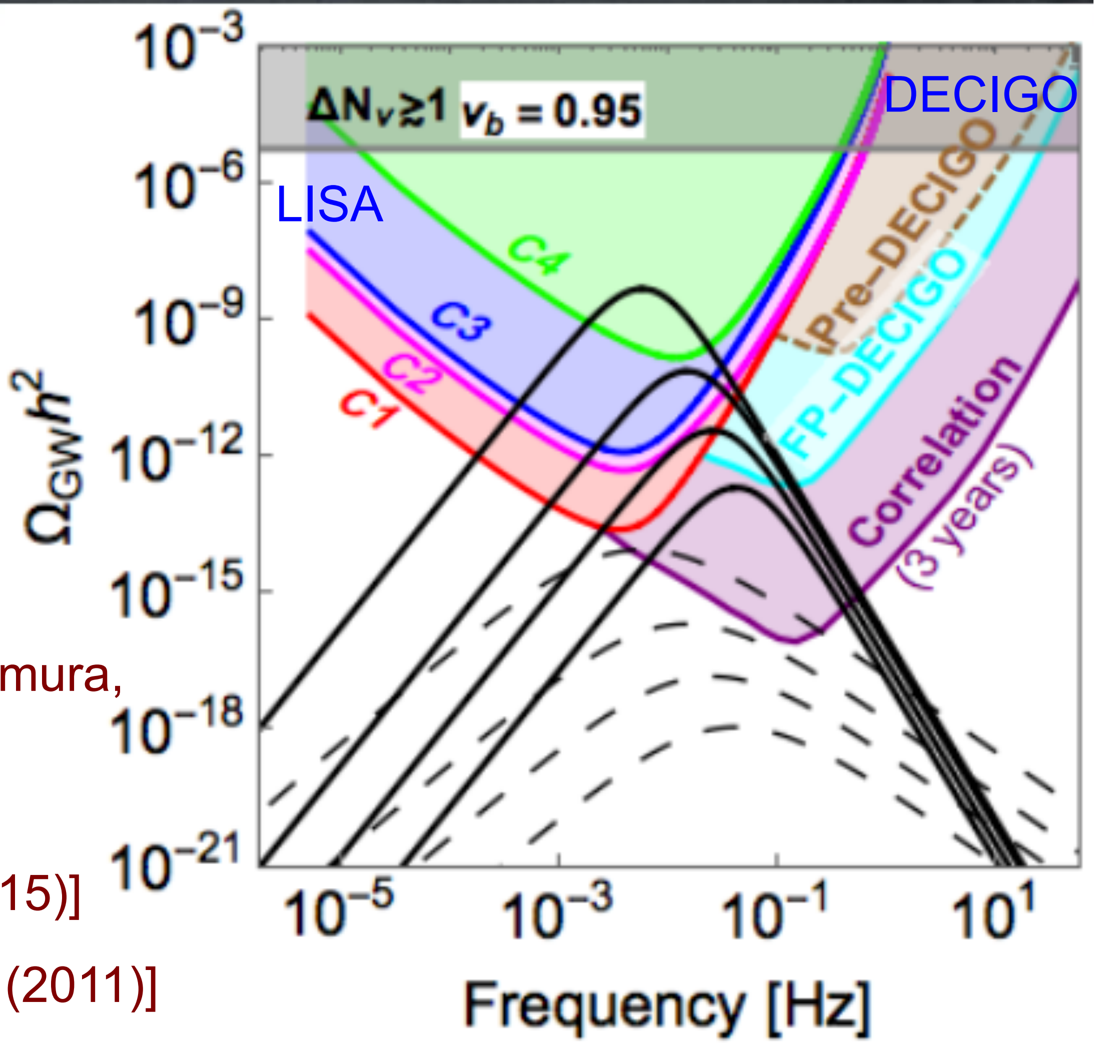
$(\sqrt{\mu_S^2}, N)$	(0 GeV, 1)	(0 GeV, 4)	(0 GeV, 12)	(0 GeV, 60)
m_S	510 GeV	361 GeV	274 GeV	183 GeV
φ_c/T_c, T_c	1.62, 119 GeV	2.03, 102 GeV	2.54, 85.6 GeV	3.65, 61.5 GeV
$(\alpha, \tilde{\beta})$, T_t	(0.0303, 3320), 111 GeV	(0.0695, 2180), 92.5 GeV	(0.164, 1600), 74.8 GeV	(0.739, 1090), 50.3 GeV

- CSI $O(N)$ models:

$(\sqrt{\mu_S^2}, N)$	(100 GeV, 1)	(100 GeV, 4)	(100 GeV, 12)	(100 GeV, 60)
m_S	524 GeV	380 GeV	299 GeV	219 GeV
φ_c/T_c, T_c	1.56, 121 GeV	1.89, 106 GeV	2.25, 92.1 GeV	2.89, 71.6 GeV
$(\alpha, \tilde{\beta})$, T_t	(0.0272, 4380), 115 GeV	(0.0552, 3480), 99.5 GeV	(0.111, 3210), 85.7 GeV	(0.334, 4082), 67.2 GeV

GW spectrum in CSI $O(N)$ models

- Contribution to GWs:
  - Collision: ....
  - Sound wave: ———
  - MHD Turbulence: - - - -
  - Benchmark points:
    $N = 1, 4, 12, 60$
    from the bottom
    [Hashino, MK, Kanemura, Matsui (2016)]
- Experimental prospects:
  - LISA: [Caprini et al. (2015)]
  - DECIGO: [Kawamura et al. (2011)]



- Contribution from sound waves is dominant and detectable at future space-based interferometers, LISA and DECIGO

Model A vs. Model B: Predicted values of α and $\tilde{\beta}$ in models with singlet scalars with and without CSI

- Condition for strongly 1st OPT
  → Constraints on α and $\tilde{\beta}$ for each model

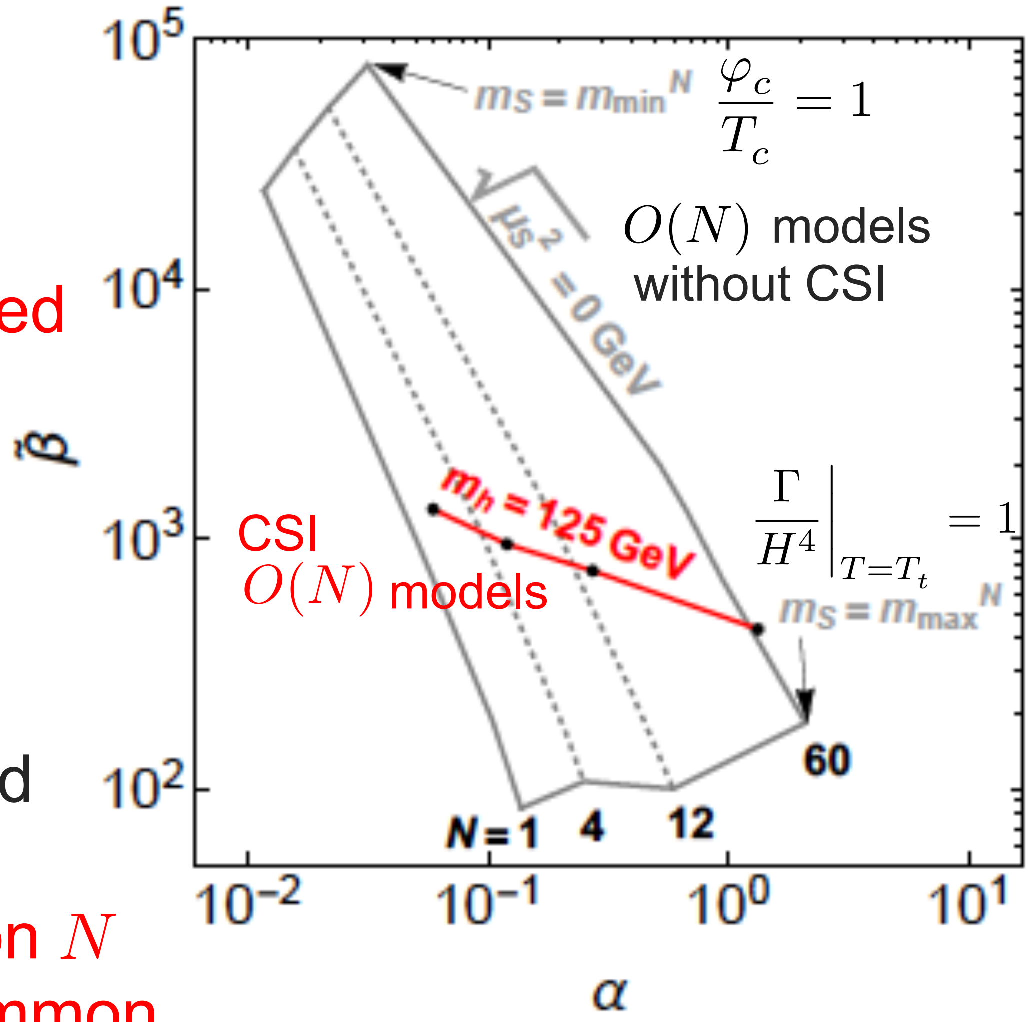
[See Hashino's poster]

$O(N)$ models without CSI

- α and $\tilde{\beta}$ to be determined by GW observation are useful measures in determining N and m_S

CSI $O(N)$ models

- Scale invariance is violated at finite temperatures
  → α and $\tilde{\beta}$ depend on N though λ_{hhh} is common

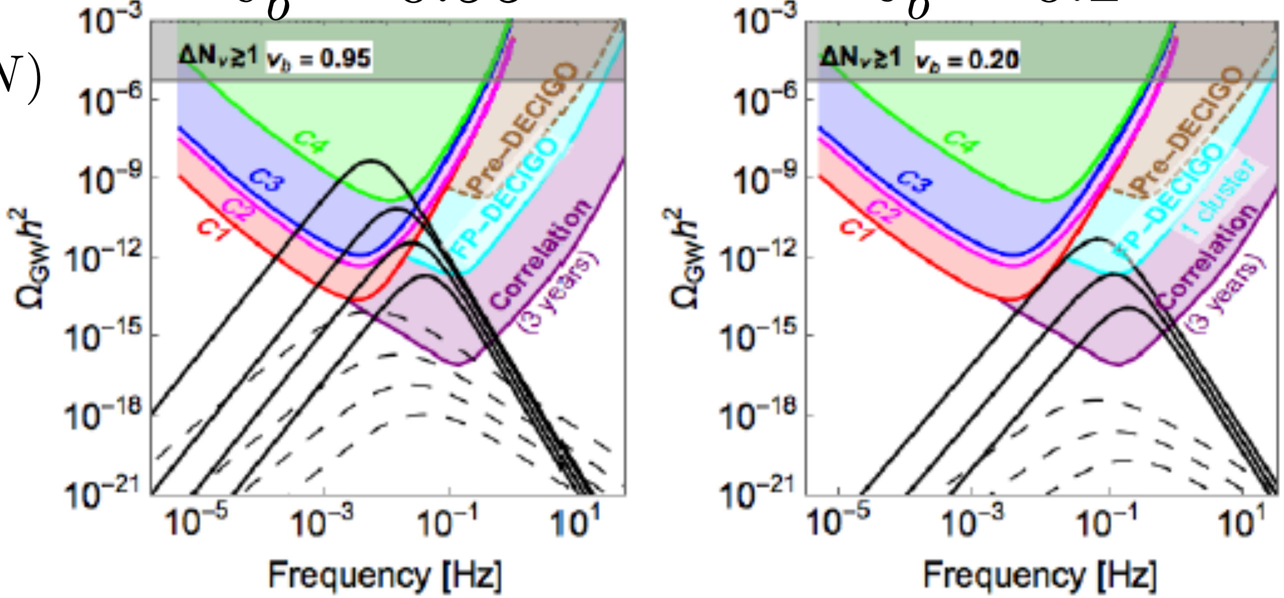


[Hashino, MK, Kanemura, Matsui (2016)]

Comparison of GW spectra

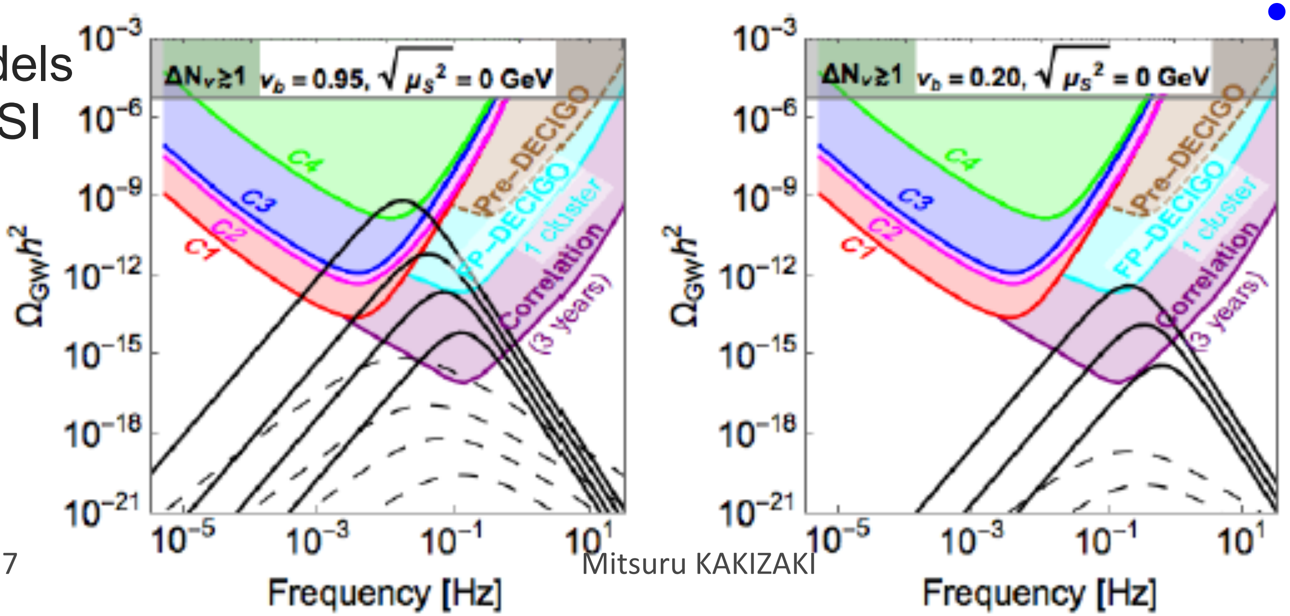
$v_b = 0.95$ $\quad$ $v_b = 0.2$

- CSI $O(N)$ models



[Hashino, MK, Kanemura, Matsui (2016)]

- $O(N)$ models without CSI $\sqrt{\mu_S^2} = 0$



- N.B. subsonic wall velocity is preferred for EWBG but not necessarily

[No (2011)]

GW spectrum for $v_b = 1$

Case of accelerating wall:

- For large α, the bubble wall can accelerate without reaching a terminal velocity

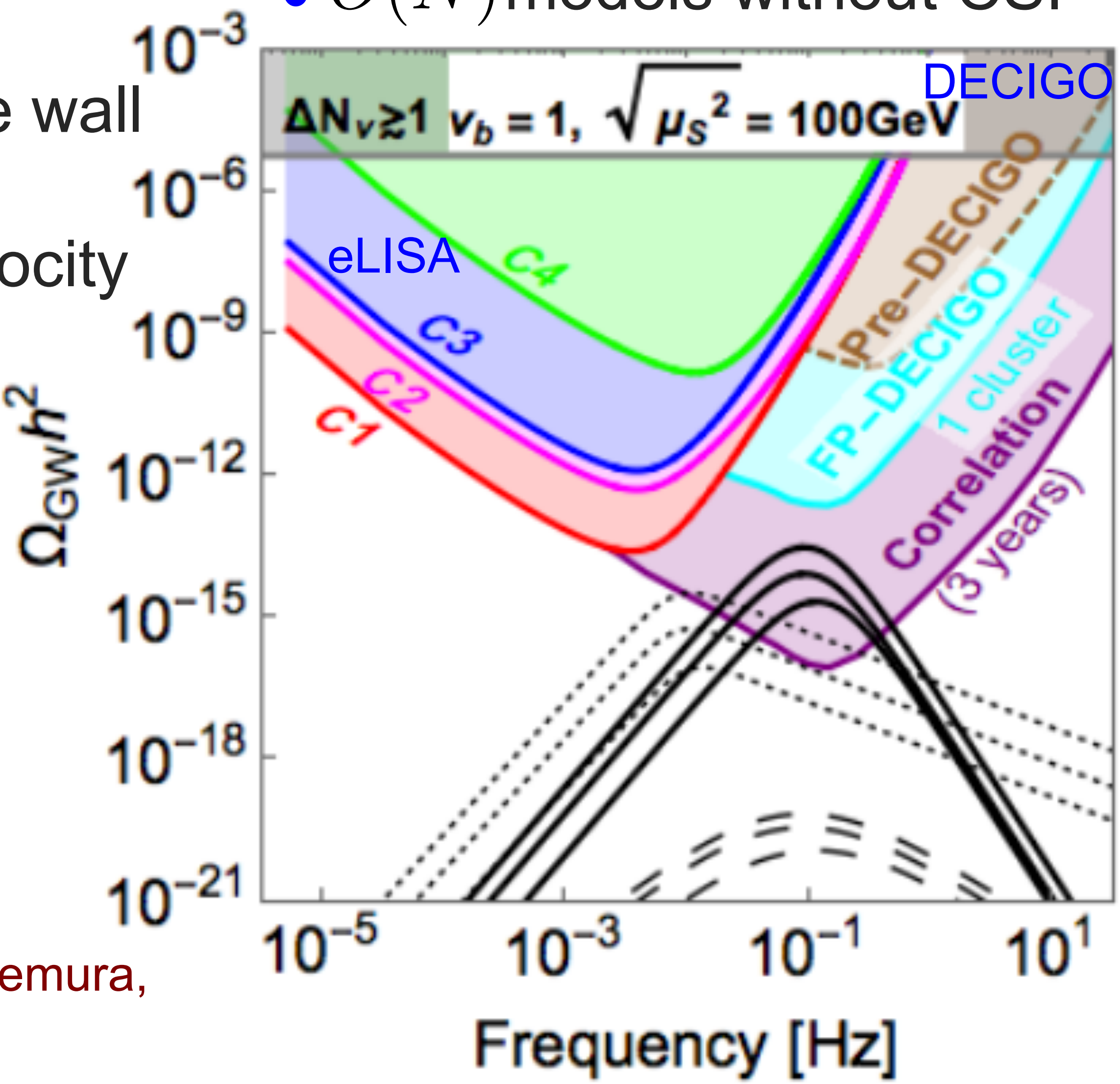
Contribution to GWs:

- Collision: ....
- Sound wave: ———
- MHD Turbulence: - - - -

- Benchmark points:
  $N = 4, 12, 60$
  from the bottom

[Hashino, MK, Kanemura, Matsui (2016)]

- $O(N)$ models without CSI



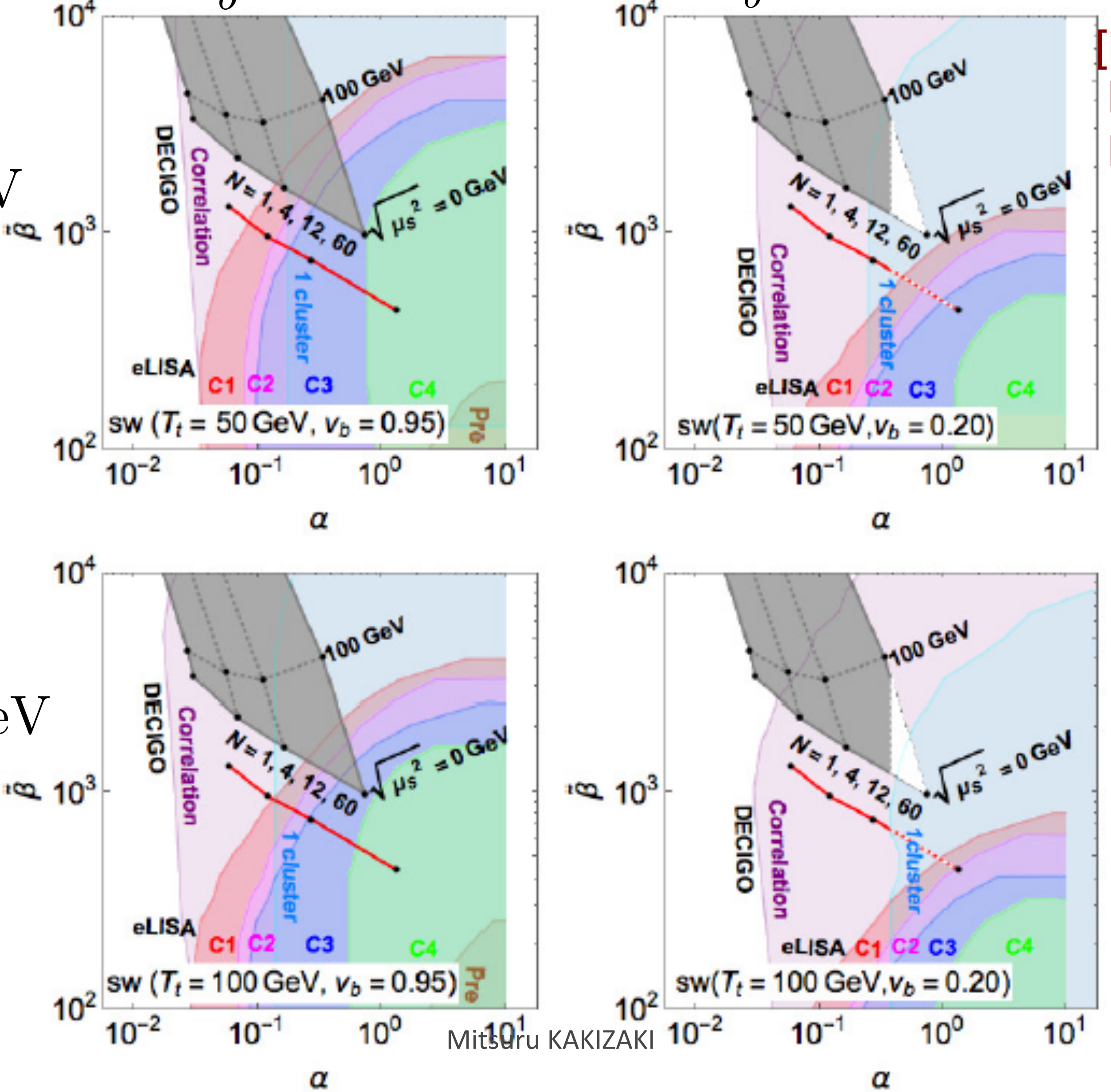
Transition temperature and wall velocity dependence of detectability of GWs

$v_b = 0.95$ $v_b = 0.2$

[Hashino, MK, Kanemura, Matsui (2016)]

$T_t = 50$ GeV

$T_t = 100$ GeV



Predicted values of α and $\tilde{\beta}$

Numerical results based on the two-field analysis

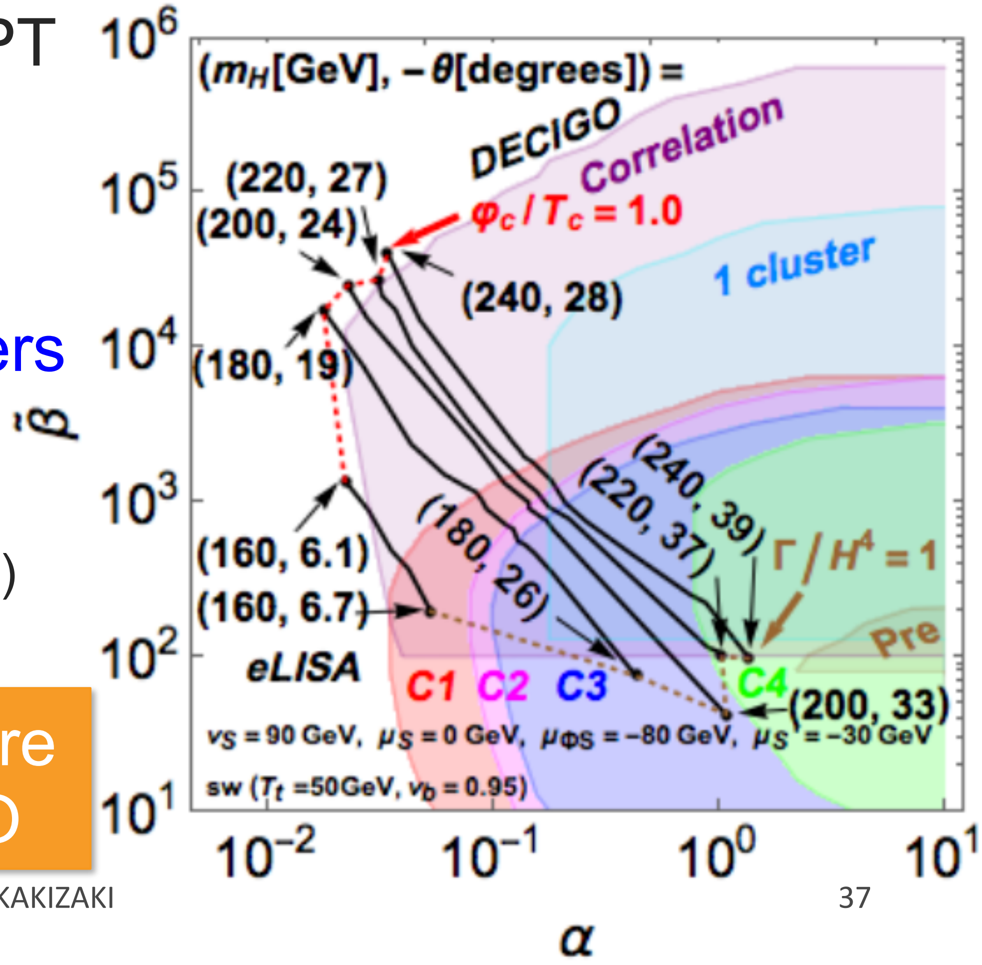
- Benchmark point

v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	-80	-30	0	[160, 240]	[-45, 0]

- Condition for strongly 1st OPT

→ Constraints on α & $\tilde{\beta}$

[Hashino, MK, Kanemura, Ko, Matsui (2016)]



Prospects of future interferometers

- LISA (C1, C2, C3, C4):

  [Caprini et al. (2015)]

- DECIGO (Pre, 1 cluster, Correlation)

  [Kawamura et al. (2011)]

GWs from 1st OPT in the HSM are detectable at eLISA and DECIGO

Landau pole in CSI model

- Large scalar couplings at the EW scale

  → Landau pole near the EW scale

N	1	4	12	60
Q	381 GeV	257 GeV	188 GeV	119 GeV
$\Lambda(\lambda_S = 0)$	5.4 TeV	17 TeV	28 TeV	33 TeV
$\Lambda(\lambda_S = 0.1)$	5.3 TeV	16 TeV	23 TeV	13 TeV
$\Lambda(\lambda_S = 0.2)$	5.2 TeV	15 TeV	19 TeV	5.4 TeV
$\Lambda(\lambda_S = 0.3)$	5.0 TeV	14 TeV	15 TeV	2.7 TeV

[Hashino, MK, Kanemura, Matsui (2016)]

LISA design

[Caprini et al (2015)]

Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1

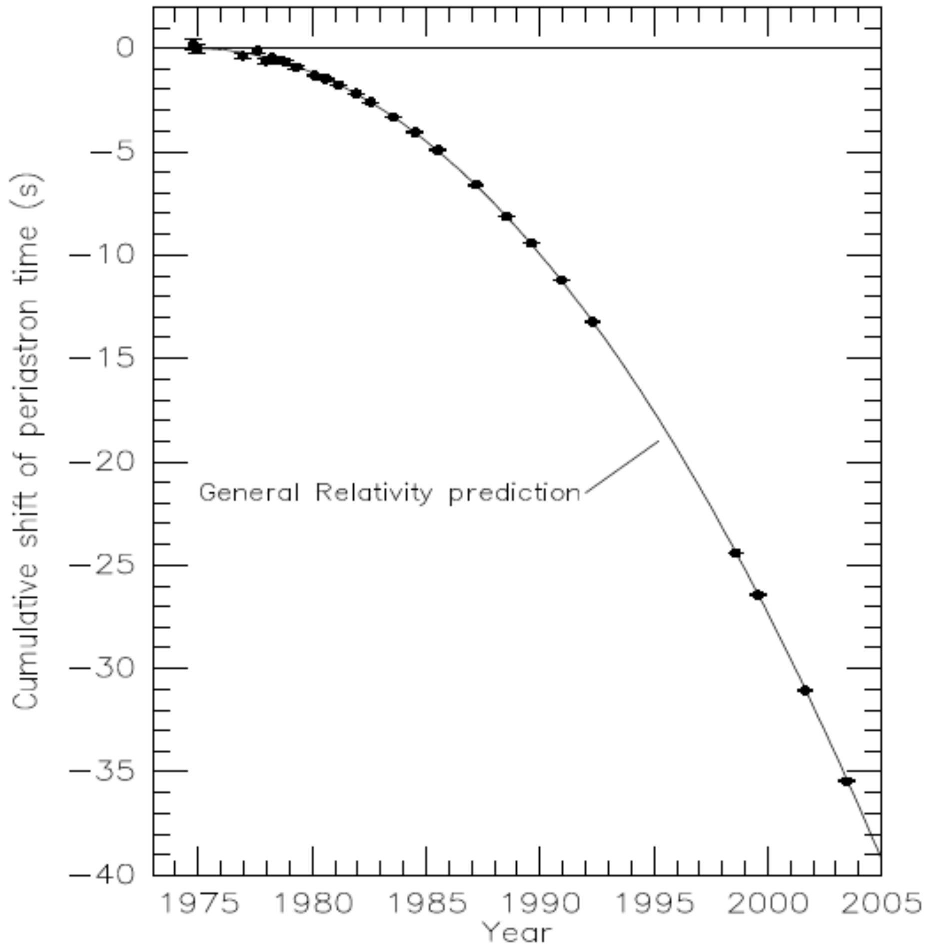
Indirect detection of gravitational waves

- Effects of gravitational waves have been observed

- In 1976, Hulse and Taylor discovered the binary pulsar (neutron star) PSR 1913+16

- The orbit is contracting due to the emission of gravitations waves

➡ 1993 Nobel prize



[Taylor,Weisberg(2004)]